



Deadwood-dominated forests buffer microclimate in exposed mountain areas

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Abstract: Microclimatic buffering is a key process that determines the regeneration potential and ecosystem stability in disturbed mountain spruce forests. Retention of standing and downed deadwood alters the balance of radiation, temperature, and humidity near the surface; however, quantitative evidence from exposed slopes in the Carpathians has been scarce. We therefore compared intact forest, deadwood-dominated forest, and open area on steep south-eastern slopes of the Western Tatras (Slovakia) using continuous measurements from 2021 to 2025. Micrometeorological stations recorded global solar radiation, air and soil temperature, and humidity at multiple heights and depths; vapour pressure deficit (VPD) was calculated at 5 cm above ground. Differences among sites were assessed using non-parametric tests. Open areas received the highest radiation loads, resulting in extreme warming of the air near the ground (up to 34 °C at 5 cm) and intense soil heating (absolute maximum of 49 °C at – 2 cm). Intact forest reduced incoming radiation and maintained the most stable conditions. Deadwood-dominated stands represented an intermediate type but repeatedly buffered extremes: summer soil maxima remained below 26 °C, and air temperatures near the ground were several degrees cooler than in the open area. In winter, snow cover largely equalised conditions, while during snow-free episodes intact forest showed stronger nocturnal cooling, whereas deadwood stands preserved milder soil minima. VPD patterns followed the same gradient, with the shortest daily duration above the threshold of 1.5 kPa in intact forest, the longest in open area, and intermediate values in deadwood stands. Overall, deadwood-dominated forest approximates, and under certain circumstances even exceeds, the buffering capacity of intact spruce stands. We conclude that retention of deadwood-dominated forests mitigates heat and drought stress, reduces thermal extremes, and provides a low-cost, ecologically grounded adaptation strategy for mountain forest management in the context of climate change.

Keywords: Climate change; Natural regeneration; Vapour pressure deficit; Soil temperature; post-disturbance succession.

1 INTRODUCTION

Climate change increasingly affects even those mountain and high-mountain ecosystems in Europe that were once considered relatively resilient (Durský et al., 2006; Hlásny et al., 2014; Dollinger et al., 2023). This also applies to the Western Carpathians, a specific high-mountain region due to its elevation and relative isolation from other major mountain ranges (the nearest being the Austrian Alps to the west). In the past, the Carpathian high-mountain zone was regarded as climatically robust, with lower mean air temperatures, reduced evapotranspiration, and higher precipitation totals driven by prevailing north-westerly airflow (Melo et al., 2013). These conditions created a specific climatic regime that, since the end of the last glacial period, allowed vegetation to expand into formerly glaciated high-mountain basins. From around 5500 BP, Norway spruce (*Picea abies*) gradually appeared first at lower slopes and later in the high-mountain belt above 1500 m a.s.l. Despite later climatic fluctuations, spruce retained its ecological optimum in the mountain forests of the Western Carpathians throughout most of the Middle and Late Holocene (Krippel, 1986; Rybníček and Rybníčková, 1986; Škvarenina et al., 2018; Melo et al., 2022).

A profound shift has occurred only in the past three decades, when unprecedented air temperatures, incursions of hot and dry air masses, and pronounced changes in both summer and winter precipitation regimes have been recorded in Central Europe, including high-mountain areas (Zeleňáková et al., 2017; Ziernicka-Wojtaszek, 2019, 2025; Lukasová et al., 2021, 2023; Micu et al., 2021; Wypych and Ustrnul, 2024). In the Western Carpathians, the impacts are spatially heterogeneous (Melo et al., 2022; Šrámek et al., 2025). In the Inner Western Carpathians, which are open towards the Danube Basin, snowfall has almost disappeared, whereas in the Outer Western Carpathians, exposed to north-westerly airflow, winter precipitation totals are increasing (Krajčí et al., 2016; Bartík et al., 2014, 2019; Blahušiaková et al., 2020; Faško et al., 2023). At the same time, greater atmospheric dynamics enhance the risk of windstorms, while summers are increasingly dominated by persistent anticyclonic conditions, blocking the inflow of moisture-rich Atlantic air masses and suppressing convective cloud formation (Vido et al., 2015). When convective conditions do occur, overheated air masses can produce exceptionally intense storms with severe abiotic impacts on forest stands (Jančo et al., 2021; Mészáros et al., 2022; Vido et al., 2024).

This evolving climatic regime increasingly exceeds both the mechanical resistance (e.g. windthrow, breakage, erosion) and physiological tolerance (e.g. hindered photosynthesis, xylem cavitation) of forest ecosystems, disrupting their homeostasis (Konôpka et al., 2019; Falťan et al., 2021; Jamnická et al., 2019; Leštianska et al., 2024; Gebauer et al., 2020). Disturbed or physiologically weakened stands become more susceptible to bark beetle outbreaks, often leading to extensive dieback (Mezei et al., 2014; Sommerfeld et al., 2021; Hlásny et al., 2021). Traditionally, forest management in such situations involved rapid salvage logging, removal of fallen timber, and site access for fire safety reasons (Kunca et al., 2019; Dobor et al., 2020; Hillayová et al., 2023). Also, this management approach was also applied to steep and exposed localities. While economically justifiable under stable climatic conditions, in today's destabilised high-mountain ecosystems it has significant drawbacks (Thorn et al., 2018; Thom et al., 2020a; Mayer et al., 2022).

One of the most important factors is the exposure of forest soil to solar radiation, which alters the thermal and moisture regime of soil and near-surface air. This leads to increased evapotranspiration and elevated root-zone temperatures (De Frenne et al., 2021; Cerioni et al., 2024; Vichta et al., 2025). Previous studies have shown that retaining deadwood on disturbed sites can markedly influence ecological conditions, benefiting both fauna and natural tree regeneration (Fleischer et al., 2017; Sandström et al., 2019; Błońska et al., 2024; Šebeň et al., 2024). Given the strong topographic effects in mountain terrain, differences in soil and near-ground microclimate between site types are likely to be even greater on steep, exposed slopes than in boreal lowlands (Bueno de Mesquita, 2018; Matev et al. 2025, Nikolova et al. 2026).

Empirical microclimatic data from exposed high-mountain spruce forests in the Carpathians remain scarce, despite several studies addressing this issue (von Arx et al., 2012; Thom et al., 2020a) and new evidence emerging from the Šumava National Park (Brůna et al., 2024). This is particularly true in terms of the potential for spruce regeneration survival in relation to levels of vapour pressure deficit (Kurjak et al., 2012), which is directly governed by the thermal and moisture parameters across differently managed sites. Our study further provides a more detailed assessment of incoming global solar radiation as a key driver shaping microclimatic regimes, complementing the analysis of thermal and moisture conditions across the sites. Addressing this knowledge gap is crucial for decisions between non-intervention management and conventional post-disturbance logging. To this end, this study evaluates and compares the microclimatic conditions of soil and near-surface air on the south-eastern slopes of the Western Tatras (Slovakia) in three site types: intact forest, deadwood-dominated forest, and open area. Specifically, we address the following research questions:

1. Does a deadwood-dominated forest buffer the near-ground microclimate of exposed mountain spruce stands compared with an open post-disturbance area, and if so, through which radiation- and structure-driven mechanisms?

2. Does this buffering reduce the intensity and duration of near-ground vapour pressure deficit (VPD) stress, thereby improving the microclimatic preconditions for Norway spruce regeneration under exposed mountain conditions?

To address these questions, we established experimental plots in July 2021 in the study area, with continuous measurements conducted until May 2025, the results of which are analysed in this paper.

2 MATERIALS AND METHODS

2.1 Locality description

The research plot Červenec (latitude 49.183617°N, longitude 19.641944°E) is located in the Western Tatras (part of the Western Carpathians) at an elevation of 1445 m a.s.l. (Fig. 1). The site lies on a typical slope of the Western Tatras, with a south-eastern exposure and an inclination of 20–33°. The entire research area is situated on a geological boundary between the Crystalline and Mesozoic zones of the Inner Western Carpathians. The predominant crystalline rocks are granodiorites and gneisses, covered by cambisol podsoles and accompanied by lithosols and rankers. Among Mesozoic rocks, calcites and dolomites dominate, with developed cambisol rendzinas (Bartík et al., 2014).

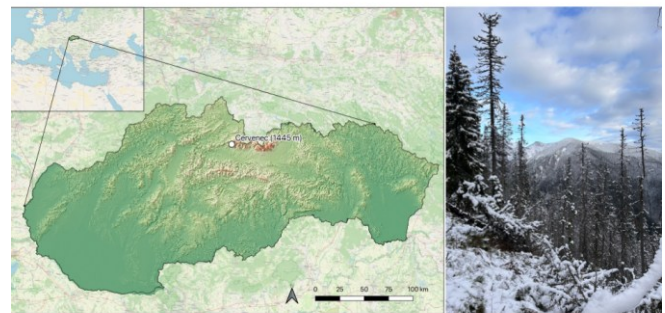


Fig. 1. Localisation of the research plot Červenec (1445 m a.s.l.) within the highest parts of the Carpathian Mts. The right panel shows a typical winter overview of the relief at the research plot and surrounding mountains.

According to Stanová and Valachovič (2002), the forest communities belong to Alpine and Carpathian subalpine spruce forests, classified as acidophilous spruce forests (*Vaccinio-Piceetea*). According to Hančinský (1972), the research site is located in the 7th spruce (*Picea*) altitudinal vegetation zone, with community types *Sorbeto-Piceetum* (60%) and *Acereto-Piceetum* (40%).

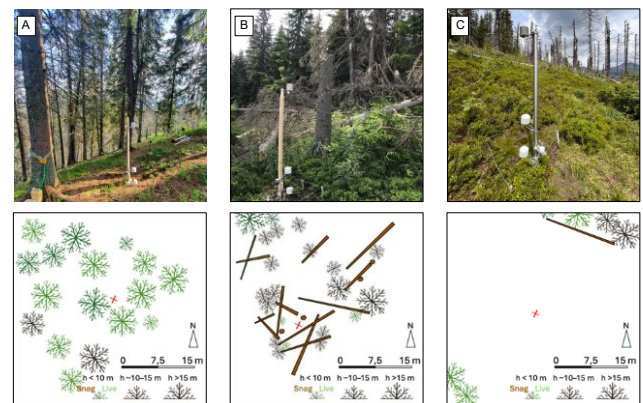


Fig. 2. Perspective and planar projection of the structural characteristics of the research plots: (a) intact forest, (b) deadwood-dominated forest, and (c) open area. In the planar projections, tree crown outlines with corresponding heights (given in the legend), fallen logs, and standing snags (circles) are shown. A red cross indicates the position of the micrometeorological station.

The predominant tree species is Norway spruce (*Picea abies* L. Karst.), which accounts for 100% of tree cover. The age of mature stands reaches up to 150 years. In the intact forest, the understorey is dominated by *Vaccinium myrtillus* L. with a cover of 20–30%. The canopy closure of the tree layer is approximately

60% (Fig. 2a). The crown base starts at a height of about 3–5 m, depending on tree height.

The open area is partly covered (50%) by *Vaccinium myrtillus* L., but *Rubus idaeus* L., *Sorbus aucuparia* L., and *Silene dioica* L. are also present (Fig. 2c).

The deadwood-dominated stand, undergoing succession, has the most diverse understorey. It consists of *Vaccinium myrtillus* L., *Rubus idaeus* L., *Sorbus aucuparia* L., *Senecio* sp. L., *Prenanthes purpurea* L., and *Luzula sylvatica* L.; to a lesser extent, also *Silene dioica* L. and *Dryopteris cartusiana* L. The total herbaceous cover reaches nearly 100% (Fig. 2b). The stand has a multi-layered structure.

2.1.1 Note on plot selection and its limitations

In the case of the open area, it should be noted that for our experiment this site was chosen as a representation of conditions arising under conventional management of post-disturbance stands, where as much timber as possible is removed and, during subsequent management, ephemeral herbs and secondary successional vegetation are regularly cleared (mown) in order to ensure regeneration. This process creates an open clearing. We acknowledge the limitations of our approach, because although our open area did originate from targeted management, it was created in 2010 (Oreňák et al. 2013). On the other hand, it is noteworthy that the vegetation on this open site has, even after 15 years, remained in the state described above. Nevertheless, for illustrating the fundamental differences that may arise between conventional post-disturbance management and management with retained deadwood, we consider our experimental design to be highly demonstrative.

2.1.2 Climate of the study area

Long-term climatic characteristics are presented based on data from the Červenec climatological station of the Institute of Hydrology, Slovak Academy of Sciences, located at an elevation of 1500 m a.s.l., with a north-facing exposure (0°). This station represents the mesoclimate of the study area, and the data span the period from 1991 to 2024. The data are routinely tested for homogeneity, and their quality is ensured through the methodological procedures of the Slovak Hydrometeorological Institute (2008).

The long-term mean annual air temperature at the reference station is 3.0 °C (Holko et al., 2025). The coldest month, on average, is January with a mean temperature of −5.7 °C, followed by February, which is 0.2 degrees colder (−5.5 °C). The absolute minimum temperature was recorded on February 28 2005, at 07:00 (−28.2 °C). The warmest month is August, with a mean temperature of 12.2 °C, followed by July, with a mean of 12.1 °C. The absolute maximum air temperature recorded at this station was 28.9 °C on July 20 2007 at 14:00 (Danko et al., 2025). From a climatological perspective, days with mean air temperatures below 0 °C occur as late as June and reappear as early as September, while in July and August there are still days when at least one hourly temperature falls below the freezing point.

Precipitation totals at the site substantially exceed atmospheric evapotranspiration demand, with a long-term mean annual sum of 1455 mm (Holko et al. 2025). The wettest months are July and June, with 191.9 mm and 159.3 mm, respectively. The wettest month on record was July 1997, when a total of 480 mm of precipitation was measured. The highest recorded hourly rainfall intensity occurred on August 5, 2015, reaching 41.8 mm, while the maximum daily total was observed on May 15, 2014, with 149.8 mm (Danko et al. 2025). The driest month is April,

with a mean precipitation sum of 84.7 mm. An interesting phenomenon is the sudden drop in precipitation in August, when, after the very wet July, the mean monthly sum falls to 126.4 mm. That is associated with the frequent occurrence of more stable weather in this area, which also explains the occasional early radiation frosts even in this summer month. The most balanced precipitation period is from October to January, when totals, most often in the form of snow, range from 98.5 to 100 mm per month.

Due to the high elevation and low temperatures, snow cover typically persists continuously from November or December until April. However, climate change increasingly causes the onset of permanent snow cover to shift into December, and depending on the course of the season, snow depth frequently reaches 200 cm or more. Conversely, especially in recent years, winters without a continuous seasonal (so-called perennial) snowpack have occurred, with alternating short periods of snow and snow-free conditions. Overall, these climatological analyses indicate that the site belongs to a cold, high-mountain climatic zone, which is also reflected in the vegetation characteristics described in the methods section. The climate of the study area is summarised in the Walter–Lieth climate diagram (Fig. 3).

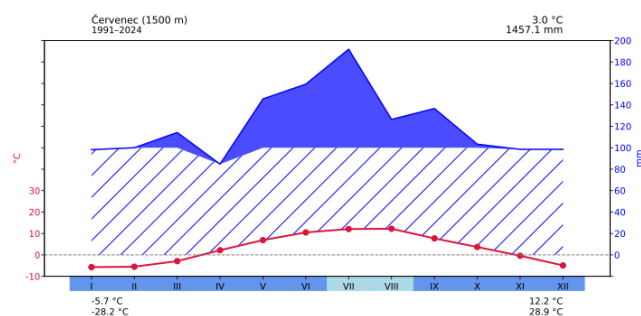


Fig. 3. Walter–Lieth climate diagram of the Červenec climatological station (1500 m a.s.l.) operated by the Institute of Hydrology, Slovak Academy of Sciences. Dark blue indicates months with at least one day of mean daily temperature below 0 °C, and light blue indicates months with occurrence of sub-zero daily minima. The red line shows mean monthly temperature, blue hatching represents monthly precipitation sums, and dark blue shading marks the super-humid zone above 100 mm. Mean annual temperature and long-term annual precipitation are given in the upper right corner, while values for the coldest and warmest months are indicated at the lower left and right sides of the diagram.

2.2 Data and data analyses

2.2.1 Microclimatic data

Microclimatic data from the research plots were obtained using micrometeorological sensors with integrated dataloggers and appropriate radiation shields, manufactured by Environmental Measuring Systems Ltd., Brno (Czech Republic). At each plot, the following devices were installed: a Minikin RTHI measuring global solar radiation, relative air humidity, and air temperature at a height of 200 cm; a Minikin THI smart sensor measuring relative humidity and air temperature at heights of 50 cm and 5 cm above ground; and a Microlog T3 datalogger with three Pt100 sensors inserted into the soil profile at depths of 2, 5, and 10 cm. The sensors were mounted on mechanically adapted masts to prevent mechanical damage and tilting of the sensors or entire micrometeorological stations caused by the long-term, gradual sliding of the thick snow cover, and to ensure that the sensors could function even when completely buried in snow.

The measurement period underlying our analyses began on July 25, 2021, and ended on May 7, 2025. For the analyses, we

used ten-minute data and daily aggregations. Central European Time (UTC +1) was applied consistently.

The measurement heights were selected with respect to the dynamics of biological processes in forests, where the herb layer and tree seedlings are located directly above the soil surface (5 cm), the layer of plants characteristic of secondary forest succession in this locality averages 50 cm, and the 200 cm level represents the meteorological standard for measuring air temperature and relative humidity. The soil depths were selected with a similar biological rationale: seedling roots (–2 cm), the root zone of fine roots of young trees and herbs (–5 cm), and –10 cm representing the main rooting layer of fine roots in the shallow ranker soils of high-mountain spruce forests.

2.2.2 Analyses of global solar radiation

We conducted analyses of solar radiation at the study plots to assess the amount and variability of incoming global solar radiation. Measurements were conducted at ten-minute intervals at a height of 200 cm above the soil surface at all three plots, using the instruments described above. Measurements in the open area (due to the character of the surroundings and the absence of trees or other obstacles that could cast shade on the global radiation sensor during the day or year) were considered as reference data against which all further radiation analyses were evaluated. For comparisons between plots, only simultaneous timestamps (the intersection of time series) were used to eliminate the effect of transient weather conditions.

As a basis for evaluating the thermal regime and also the regime of vapour pressure deficit, we assessed the amount of incoming global solar radiation (K_i) in relation to the open area. Since the global radiation sensors were installed at a height of 2 m, it is evident that the amount of intercepted or transmitted global solar radiation will fluctuate considerably in the live forest, but also, due to the character, height, and position of dead standing trees or stem remnants, in the deadwood-dominated forest. For this reason, we applied a simplified approach to evaluating the transmittance of global solar radiation, which is a commonly used metric in canopy radiation studies (Foken, 2017).

Transmittance (T) expresses the relative penetration of global solar radiation through the canopy (height >2 m) in comparison with the open area:

$$T = \frac{K_{i \text{ plot}}}{K_{i \text{ open}}} \quad (1)$$

where $K_{i \text{ plot}}$ denotes the incoming radiation measured by the global radiation sensor at the plot, and $K_{i \text{ open}}$ denotes the global radiation measured by the sensor in the open area. Transmittance (T) was determined for the entire period such that, for each day-time ten-minute interval $K_{i \text{ open}} \geq 50 \text{ W m}^{-2}$, the ratio of radiation at the studied plot to that at the open area was calculated. All values were subsequently grouped by hour of the day across the whole period, and the median for each hour was determined, yielding a representative diurnal profile of (τ).

The daily sum of incoming global solar radiation was expressed in ($\text{MJ m}^{-2} \text{ day}^{-1}$). The results are presented in the form of boxplots of paired days across plots. This provides information on the similarity or dissimilarity of the studied plots in terms of the amount of incoming energy at the assessed active surface or at the vertical profile of the near-ground atmosphere, as described above. Differences between paired datasets were evaluated using the non-parametric Wilcoxon signed-rank test (Wilcoxon, 1945).

The potential of the incoming solar radiation was calculated based on astronomical parameters for the site ($\phi = 49,1836^\circ \text{ N}$, $\lambda = 19,6419^\circ \text{ E}$) on 3 July 2022 (DOY = 184). The reason for analysing this day is that on that day, a detailed analysis of the air and surface temperature regime was carried out, as will be shown later on.

Solar elevation (altitude) and azimuth were determined at 30-minute intervals from standard relationships for the hour angle, declination, and equation of time.

The potential on a horizontal surface was expressed as $\cos \theta_z$, where θ_z is the zenith angle. For an inclined surface oriented to the southeast (surface azimuth $\gamma_p = 135^\circ$) with an average slope $\beta = 25^\circ$, the general relationship of the Liu–Jordan model (Liu and Jordan, 1963) was used to compute the incidence angle θ_i .

The relative gain of the inclined surface compared with the horizontal surface was expressed by the ratio:

$$R_b = \frac{\cos \theta_i}{\cos \theta_z} \quad (2)$$

which indicates the percentage change in incoming direct radiation under identical atmospheric conditions.

2.2.3 Air and soil temperature regime

The following indicators of the microclimatic regime were evaluated: mean daily air temperature at heights of 200 cm, 50 cm, and 5 cm above the ground surface, and mean daily soil temperature at depths of 2 cm, 5 cm, and 10 cm. Mean daily values were calculated as the arithmetic average of all available measurements during the observation period from July 25 2021, to May 7 2025.

To assess the extremity of the temperature regime, we analysed average values of daily minimum air temperatures during the meteorological winter (December to February) and maximum air temperatures during the meteorological summer (June to August). The same approach was applied to evaluate the soil temperature regime across all three investigated sites: intact forest, deadwood-dominated forest, and open area.

In addition, we identified the absolute minimum and maximum air and soil temperatures recorded at each site throughout the entire monitoring period.

For comparison of microclimatic conditions within the broader exposure context, the mean daily air temperature at 200 cm was also analysed from the nearby meteorological station Červenec for the corresponding period (July 25, 2021 – May 7, 2025).

To assess the statistical significance of differences among the plots, we employed the non-parametric Kruskal–Wallis test (Kruskal and Wallis, 1952), which enables a global comparison of all three groups. In cases where the test was significant ($p < 0.05$), we subsequently applied the Mann–Whitney U test for pairwise comparisons between plots (Mann and Whitney, 1947). The p-values were adjusted using the Bonferroni correction (Bonferroni, 1936) in order to minimise the risk of false positive significance.

2.2.4 Vapour Pressure Deficit (VPD) Analysis

In our analyses, the vapour pressure deficit (VPD) was calculated at 5 cm above ground level. The rationale for focusing on this height lies in the central research question of this study, which aims to assess whether the microclimate of deadwood-dominated stands can provide conditions suitable for the survival of young trees and seedlings. Since the natural microclimatic niche of seedlings is logically concentrated in the lowest vertical

stratum of the profile, we restricted the VPD evaluation to this height.

The vapour pressure deficit (VPD) was calculated for each measurement interval using the following relationship:

$$\text{VPD} = e_s(t_a) - e_a \quad (3)$$

where:

$$e_s(t_a) = 0,6108 \cdot \exp\left(\frac{17,27 \cdot t_a}{t_a + 237,3}\right) \quad (4)$$

represents the saturation vapour pressure [kPa] at air temperature t_a [°C], and

$$e_a = e_s(t_a) \frac{RH}{100} \quad (5)$$

represents the actual vapour pressure [kPa] at relative humidity RH [%].

Only data from the meteorological summer (June–August) were included in the analysis. A VPD threshold of 1.5 kPa was selected as the approximate level above which stomatal closure occurs in spruce (Kurjak et al., 2012; Zweifel et al., 2002). Subsequently, the following metrics were derived for each plot, for every day of the year (DOY) and for each year of observation:

1. Daily absolute maximum VPD (the highest value observed during the day),
2. Fraction of the day above 1.5 kPa, expressed as [h] by converting the proportion of records exceeding the threshold into hours.

These daily values were then averaged across all available summers for the respective DOY and plot. Two metrics are presented in the graphical section:

- (i) absolute daily maxima of VPD – the highest VPD values observed for each DOY and plot across all years,
- (ii) mean time above 1.5 kPa [h] – for each DOY and plot, the average fraction of records exceeding the threshold (averaged across years) converted into hours per day (fraction $\times 24$), assuming uniform sampling throughout the day.

2.2.5 Analysis of microclimatic regime during representative weather episodes

To assess the detailed diurnal dynamics of the microclimate, three meteorologically typical days were selected for the studied mountain region. The criteria for selection were as follows:

1. A typical summer sunny day with a mean daily temperature exceeding the long-term average for the respective month,
2. A typical winter sunny frost day without snow cover, with a mean daily temperature lower than the long-term monthly average,
3. A typical winter sunny frost day with snow cover, also with a mean daily temperature lower than the long-term monthly average.

For the winter episodes, two consecutive days were analysed in order to capture pronounced nocturnal micrometeorological dynamics. The following episodes were selected:

- 20–21 February 2025 (sunny frost day without snow cover),
- 10–11 March 2022 (sunny frost day with snow cover),
- 3 July 2022 (sunny hot summer day).

For each of these days (or pairs of days in winter), combined thermo-isopleths of air and soil temperature were constructed for the vertical profile from –10 cm soil depth to 200 cm above the ground (y-axis), and for the temporal range from 00:00 to 23:59 of the following day (or the second day in winter cases). Thermo-isopleth diagrams were generated from measured temperature values arranged into a time–height/depth matrix. The diagrams

were displayed as colour-filled contour plots using Matplotlib's contourf function, with contour levels defined at 0.5 °C intervals. The visual representation between the available sensor levels and time steps was produced by bilinear interpolation within the time–height/depth plotting domain. No additional interpolation, smoothing, or gap-filling of the original temperature data was applied prior to plotting; the contour plots were based on the measured values at the available sensor levels and time steps.

3 RESULTS

3.1 Analysis of global solar radiation

For a thorough assessment of the specific thermal regime of the studied plots, it is first necessary to consider the character and amount of incoming solar energy, which we evaluated by comparing the amount and intensity of global solar radiation. The mean daily sum of global radiation incident on the open area (reference site) during the observation period was 8.5 MJ m^{–2} day^{–1}. In contrast, in the intact forest, this value was only 2.8 MJ m^{–2} day^{–1}. In the deadwood-dominated forest, the incident energy was lower than in the open area (7.84 MJ m^{–2} day^{–1}). Although these values may appear similar at first glance (Fig. 4), the Wilcoxon signed-rank test revealed significant differences between the open and the deadwood-dominated forest.

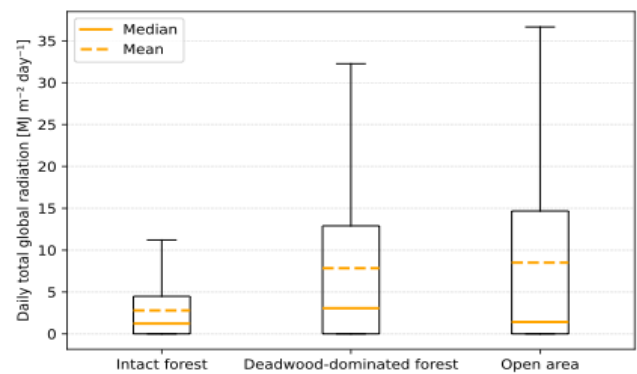


Fig. 4. Boxplots of daily incoming solar radiation during the study period.

The lower median value in the open area compared with the deadwood-dominated forest reflects the strongly skewed distribution of daily radiation sums. In the open area, a limited number of clear-sky days with very high radiation loads increased the mean daily sum, whereas the median remained low because more than half of the days had relatively low incoming radiation, especially under cloudy, low-sun-angle, or winter conditions. In contrast, the deadwood-dominated forest showed a different distribution shaped by heterogeneous shading from standing snags and remaining structural elements, which reduced extreme high values but did not necessarily reduce the central part of the distribution in the same way.

We can therefore conclude that the amount and distribution of daily incoming solar radiation differed substantially among the plots.

A detailed comparison of transmitted versus intercepted radiation by the canopies of living trees (intact forest) or by standing snags and dead crowns (deadwood-dominated forest) is provided in the graph of median diurnal transmittance (Fig. 5), relative to the open area without shading elements. Light penetration is most strongly blocked in the intact forest (on average, only 25% of the open-site energy is transmitted). In contrast, the deadwood-dominated forest still receives substantially higher energy inputs, with mean transmittance ranging from 75% to 90% of

that of the open site. Within a given day, however, we observed pronounced fluctuations (particularly in the deadwood-dominated forest), highlighting the considerable influence of shadows cast by surrounding standing dead trees and trunk remnants. This explains the statistical significance of the differences between the deadwood-dominated forest and the open area described above.

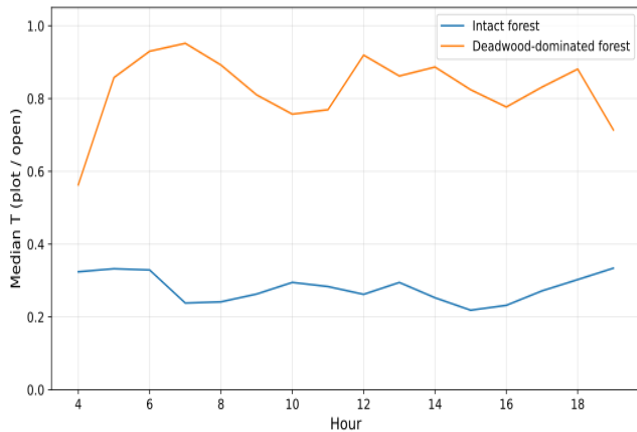


Fig. 5. Diurnal median transmittance (T) of global solar radiation relative to the open area.

Due to canopy structure, crown base height, site exposure, slope inclination, and the nature of plot-specific differences, substantial seasonal variations are also evident. During summer, when solar energy input reaches its annual maximum, intriguing differences emerge in the diurnal course of radiation among the sites. These differences are of particular importance as they fundamentally influence the extremity of the thermal regime in the near-surface atmosphere and soil.

As an illustrative example, Fig. 6 shows the diurnal course of global solar radiation on 3 July 2022, representing a typical hot summer day with a mean daily temperature exceeding the long-term monthly average. This day is analysed in more detail in the subsequent section on diurnal microclimatic dynamics of the atmospheric boundary layer and soil. On this day (DOY 184), the angle of direct solar incidence at solar noon relative to the plane of the sensor was 19° , representing one of the highest attainable solar elevations. Due to the requirement of selecting a cloud-free day, it was unfortunately not possible to use a date closer to the summer solstice (22 June 2022). At the horizontally levelled radiation sensors, 90.1% of the astronomical potential of summer solstice radiation was recorded at noon on this latitude. The maximum hourly intensity of solar radiation during this day was 882.72 W m^{-2} at noon.

As shown in Fig. 6, the radiation intensity at that time fluctuated markedly at both forested sites. In the deadwood-dominated forest, radiation increased again to its maximum (849 W m^{-2}) after being strongly shaded at 11:00 (275 W m^{-2}). Shortly before, a maximum was reached in the intact forest at 11:30 (626 W m^{-2}), followed by a steep decline to 202 W m^{-2} at 12:30. A subsequent increase to a second maximum of 593 W m^{-2} at 13:30. This represents a fascinating diurnal radiation pattern, demonstrating that light patches created by the partial canopy closure of the intact forest (canopy cover ~ 0.6) constitute a strong but temporally variable source of incoming energy, which in turn influences the diurnal course of the microclimatic regime of the boundary layer, as shown further below. At the same time, this example illustrates that even standing dead trees can, under

certain conditions, exert a pronounced shading effect and substantially influence the transmission of solar energy.

When also considering the site's slope (mean inclination 25%) and south-eastern exposure, the actual solar input on the open area during DOY 184 was higher than on the horizontal plane of the radiation sensor, amounting to 94.7% of the astronomical potential compared to 90.1% on the horizontal. This clearly indicates that site exposure and slope have a substantial impact on the amount of incident solar radiation, which is further strongly modified by the structural characteristics of each studied plot.

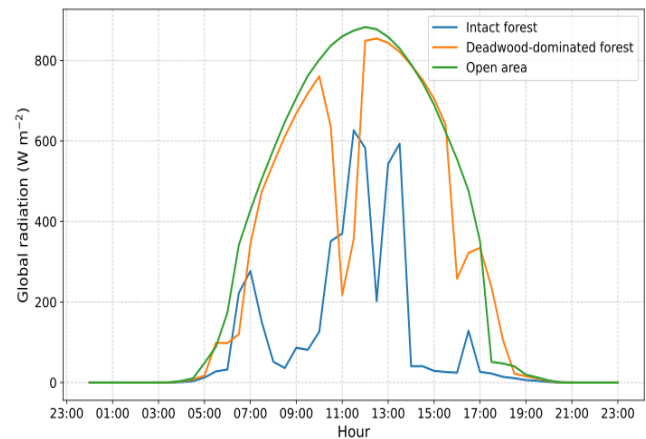


Fig. 6. Daily course of incoming global solar radiation on the studied plots on 3 July 2022.

3.2 Air and soil temperature regime during the observation period

Although mean values smooth short-term extremes, they provide an important baseline characterization of the overall microclimatic regime of the studied post-disturbance habitats and allow comparison among plots and with the nearby reference climatological station. The mean air temperature during the study period ranged from 4.47°C (intact forest) to 5.26°C (deadwood-dominated forest) at 200 cm, 4.59°C (intact forest) to 5.39°C (deadwood-dominated forest) at 50 cm, and 5.09°C (intact forest) to 5.66°C (open area) at 5 cm above ground (Table 1). At a height of 200 cm, all three study sites were warmer than the reference climatological station Červenec (3.9°C for the same period). When compare open area (4.66°C) with the average at the climatological station Červenec (in the same period), we see that the temperature difference can be partly attributed to the slightly higher elevation of the Červenec station (1500 m a.s.l. vs. 1445 m a.s.l. at our sites), explaining $\sim 47\%$ of the deviation based on the standard lapse rate (0.65°C per 100 m). The remaining $\sim 53\%$ is attributable to site-specific exposure, with the south-eastern slope ($\sim 25^\circ$) accounting for an additional warming effect of $\sim 0.40^\circ\text{C}$.

At 200 cm, mean temperatures differed substantially among the sites (range: 0.79°C), with the intact forest being the coolest (4.47°C) and the deadwood-dominated forest the warmest (5.26°C). Smaller differences were observed at 50 cm (range: 0.80°C), while the lowest differences occurred at 5 cm above ground (range: 0.57°C). This paradox—contrary to expectations that near-surface temperatures would diverge most strongly—may be explained by the long-lasting perennial snowpack in these altitudes, which insulated and homogenised temperatures close to the ground compared with higher profiles. This will be addressed in greater detail later in the paper.

Table 1. Mean air and soil temperatures at the study plots (2021 – 2025).

	Soil depth			Air height		
	-10 cm	-5 cm	-2 cm	5 cm	50 cm	200 cm
Intact forest	5.71	5.62	5.65	5.09	4.59	4.47
Dead wood	5.6	5.7	5.64	5.09	5.39	5.26
Open area	6.84	6.97	6.98	5.66	4.84	4.66

In the soil, the inter-site differences are much pronounced (Table 1). Also, the mean soil temperatures at all depths are higher compared to the air temperatures. In general, the open area was consistently warmer at all soil depths, with the highest mean temperature recorded at –2 cm (6.98 °C), while the lowest occurred in the deadwood-dominated forest at –10 cm (5.6 °C).

Particularly noteworthy is the larger inter-site range of soil temperatures across all depths (1.24–1.34 °C) compared with the ranges of air temperature recorded at all heights (0.57–0.80 °C). This difference highlights the pronounced influence of exposure-related microclimate. Soil is subject to greater contrasts in heating than air, as on sloping terrain, solar radiation directly warms the ground surface. In contrast, the near-surface air layer is more effectively ventilated, mixed, and transported upslope by convective flows. That leads to reduced mean differences in air temperature between sites compared to soil.

When considering extreme values, differences between the sites became more pronounced (Table 2). During the summer, the highest mean maximum air temperature was recorded in the open area, with a mean maximum of 26.07 °C at a height of 5 cm and an absolute maximum of 37.76 °C. In contrast, mean maxima at 5 cm were substantially lower in the intact forest (19.24 °C) and deadwood-dominated forest (21.16 °C). During winter, mean daily minimum air temperatures were lowest in the intact forest (–5.71 °C at 200 cm, –4.65 °C at 50 cm, –2.32 °C at 5 cm). However, the lowest absolute minima were observed in the deadwood-dominated forest (–18.71 °C at 50 cm) and the open area (–17.41 °C at 50 cm), reflecting stronger nocturnal cooling outside the forest. This pattern is linked to stronger radiative cooling, whereas reduced ventilation in closed stands suppresses extremes despite local cold-air pooling.

For soils, the highest mean summer maxima were again observed in the open area, particularly at a depth of –2 cm (33.04 °C), where the absolute maximum reached 49.16 °C, reflecting full solar exposure without vegetation cover. Forest soils remained much cooler, with mean maxima at –2 cm of 20.23 °C (intact forest) and 16.99 °C (deadwood-dominated forest).

During winter, the mean daily soil minima were lowest in the intact forest (0.04 °C at –2 cm, 0.14 °C at –5 cm), with the absolute minimum at –2 cm reaching –7.05 °C.

Statistical tests (Kruskal–Wallis, Mann–Whitney with Bonferroni correction) confirmed significant differences between sites, particularly during summer and in surface layers. The deadwood-dominated forest repeatedly appeared as an intermediate type, substantially buffering extremes compared with the open area – especially in soil temperatures.

3.3 Vapour pressure deficit (VPD) characteristics at 5 cm above ground

The evaluation of the thermal regime highlights extreme conditions near the soil surface during summer. These conditions are reflected in the vapour pressure deficit (VPD), a key factor controlling stomatal conductance of Norway spruce, the main edifier of the ecosystem. Based on published findings, a threshold of 1.5 kPa was applied, above which stomata close and physiological processes are restricted. In addition to this threshold exceedance, we report both the maximum daily VPD and the average duration (h day^{–1}) above the threshold during the summer season.

The mean duration of VPD above 1.5 kPa was longest in the open area (9.77 h day^{–1}), intermediate in the deadwood-dominated forest (7.26 h day^{–1}), and shortest in the intact forest (3.85 h day^{–1}). A similar pattern emerged for maximum daily VPD, which averaged 3.74 kPa in the open area, 2.78 kPa in the deadwood-dominated forest, and 2.04 kPa in the intact forest. These results indicate substantially higher microclimatic drought stress in the open area, driven by elevated air temperature and reduced humidity during sunny summer days.

Overall, the intact forest most effectively buffered high VPD stress, while the deadwood-dominated forest represented an intermediate state. Although less stable than an intact forest, it clearly reduced atmospheric stress compared with the open area, acting as a microclimatic compromise between closed forest and open landscape conditions (Fig. 7).

Table 2. Meteorological summer maxima and winter minima of air and soil temperatures (*t*).

Meteorological summer maximum temperature													
	Soil depth						Air height						
	-10 cm		-5 cm		-2 cm		5 cm		50 cm		200 cm		
	<i>t</i> _{max} ^{abs}	<i>t</i> _{max} ^{mean}	<i>t</i> _{max} ^{abs}	<i>t</i> _{max} ^{mean}	<i>t</i> _{max} ^{abs}	<i>t</i> _{max} ^{mean}	<i>t</i> _{max} ^{abs}	<i>t</i> _{max} ^{mean}	<i>t</i> _{max} ^{abs}	<i>t</i> _{max} ^{mean}	<i>t</i> _{max} ^{abs}	<i>t</i> _{max} ^{mean}	<i>t</i> _{max} ^{abs}
Intact forest	17.18	12.74	26.87	17.79	40.22	20.23	31.48	19.24	28.82	18.06	27.14	17.63	
Dead wood	19.72	13.48	25.01	15.34	29.27	16.99	34.96	21.16	32.2	21.41	27.55	18.77	
Open area	25.08	19.31	33.23	24.9	49.16	33.04	37.76	26.07	30.34	20.9	27.62	18.8	
Meteorological winter minimum temperature													
	Soil depth						Air height						
	-10 cm		-5 cm		-2 cm		5 cm		50 cm		200 cm		
	<i>t</i> _{min} ^{abs}	<i>t</i> _{min} ^{mean}	<i>t</i> _{min} ^{abs}	<i>t</i> _{min} ^{mean}	<i>t</i> _{min} ^{abs}	<i>t</i> _{min} ^{mean}	<i>t</i> _{min} ^{abs}	<i>t</i> _{min} ^{mean}	<i>t</i> _{min} ^{abs}	<i>t</i> _{min} ^{mean}	<i>t</i> _{min} ^{abs}	<i>t</i> _{min} ^{mean}	<i>t</i> _{min} ^{abs}
Intact forest	-1.69	1.16	-6.73	0.14	-7.05	0.04	-17.15	-2.32	-16.79	-4.65	-16.24	-5.71	
Dead wood	-1.03	1.25	-1.94	0.96	-3.03	0.7	-9.1	-0.94	-18.71	-3.81	-16.55	-5.94	
Open area	-1.16	1.03	-3.2	0.54	-6.35	0.11	-12.24	-0.63	-17.41	-3.9	-16.43	-5.77	

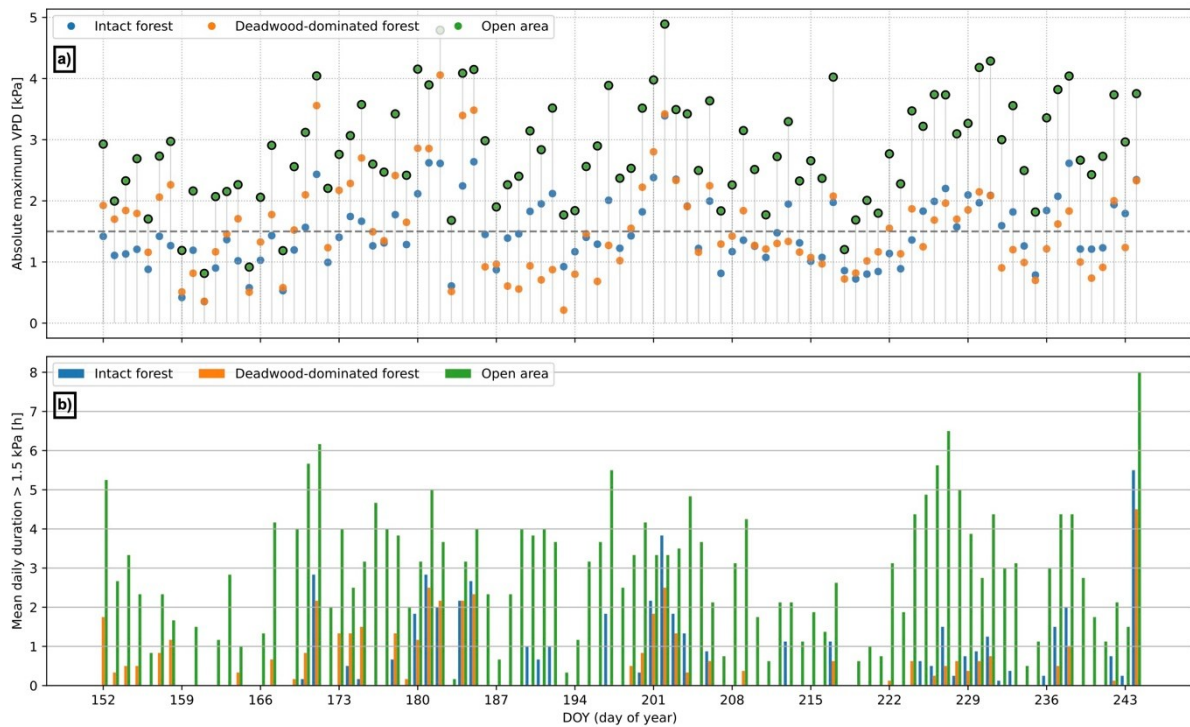


Fig. 7. Vapour pressure deficit (VPD) at 5 cm above ground on the studied plots. (a) Absolute daily maxima of VPD with indication of the threshold of 1.5 kPa, (b) mean daily duration of VPD exceeding 1.5 kPa during the meteorological summer. The black rounds in a) represent the locality with the highest value of the VPD.

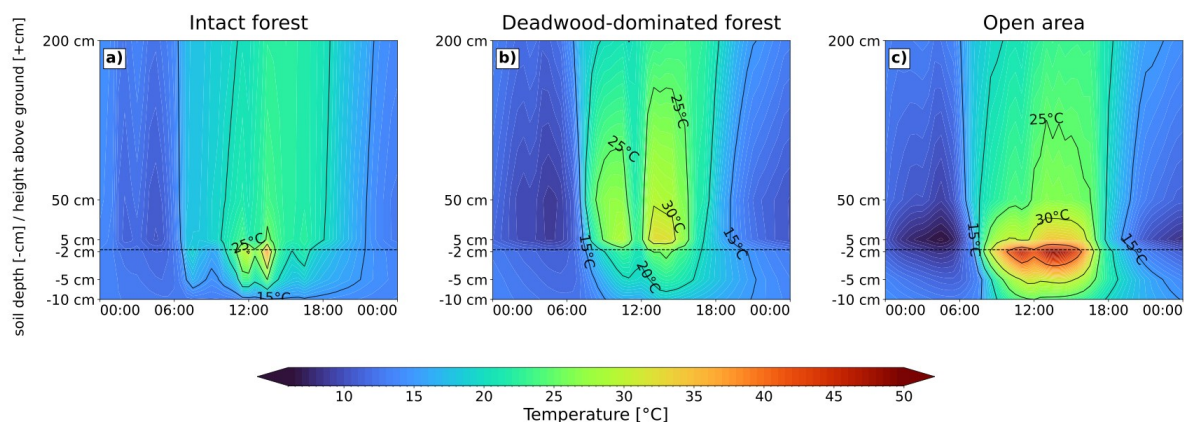


Fig. 8. Daily course of the air and soil temperature on a sunny summer day, 3 July 2022. a) intact forest, b) deadwood-dominated forest, c) open area.

3.4 Microclimatic regime during typical weather episodes

To illustrate the divergent dynamics of the thermal regime among the studied sites, we analysed air and soil temperature profiles in high temporal resolution during three representative synoptic situations: (1) a hot summer day with minimal cloud cover, (2) a frosty winter day with snow cover, and (3) a frosty winter day without snow cover.

On July 3, 2022, extreme diurnal fluctuations in air and soil temperatures were observed (Fig. 8). In the intact forest (Fig. 8a), midday sunflecks penetrating through canopy gaps (Fig. 6) temporarily heated the topsoil (–2 cm) to 37.9 °C. However, the warming effect did not extend below a depth of 5 cm, confirming the transient nature of this phenomenon. Air temperature within the vertical profile remained relatively stable between 20–23.7

°C from 09:30 to 18:00, while nocturnal minima did not fall below 10.4 °C, reflecting the canopy's strong insulation against longwave radiation losses.

In contrast, the open area (Fig. 8c) displayed the most extreme conditions. The maximum soil temperature at a depth of –2 cm reached 49.1 °C, with values above 40 °C persisting for over five hours. Even at –5 cm depth, temperature peaked at 31.4 °C, while at –10 cm the maximum was 25.4 °C, far exceeding values in the intact forest (18.6 °C). The air temperature at 5 cm reached 34.3 °C, whereas at 200 cm, it peaked at 23.4 °C, only slightly above the temperature in the intact forest (22.5 °C). Nighttime minima, however, were considerably lower in the open area (6.4 °C at 5 cm) compared to the intact forest (10.4 °C).

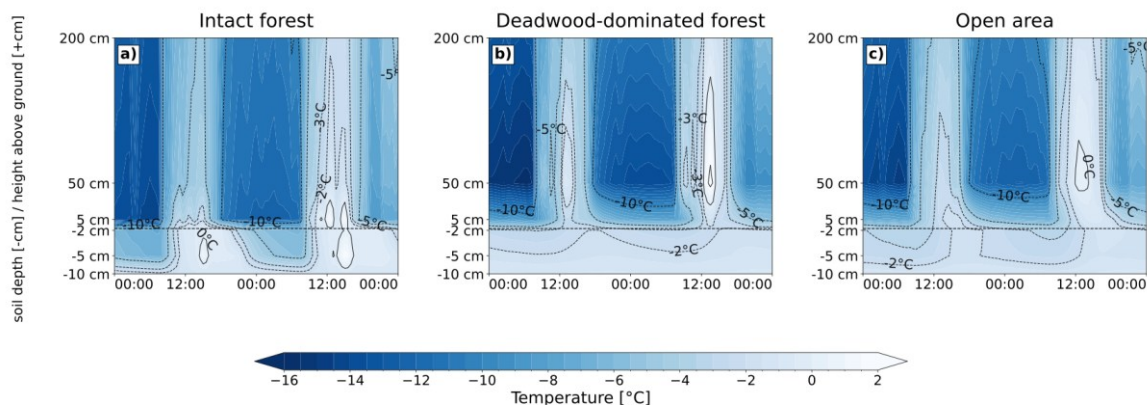


Fig. 9. Daily course of the air and soil temperature during the no-snow winter episode on 20–21 February 2025. a) intact forest, b) deadwood-dominated forest, c) open area.

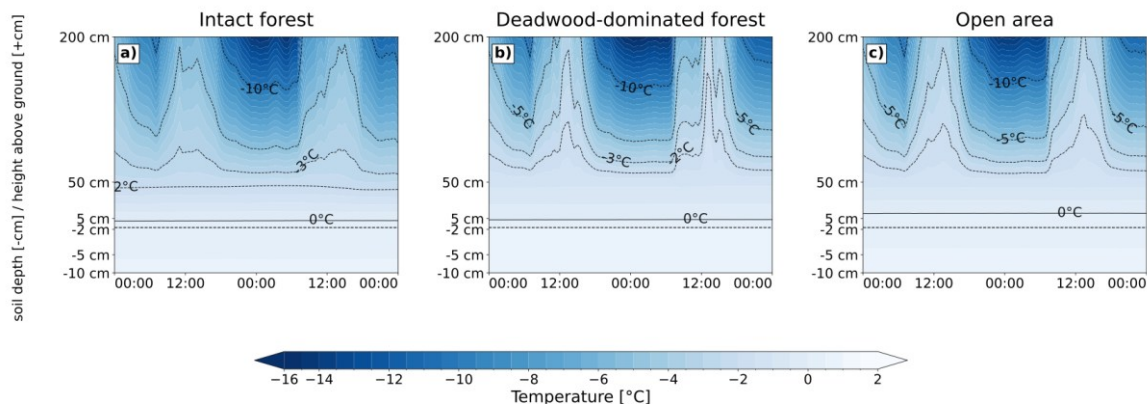


Fig. 10. Daily course of the air and soil temperature during the snow winter episode on 10–11 March 2022. a) intact forest, b) deadwood-dominated forest, c) open area.

The deadwood-dominated forest (Fig. 8b) showed intermediate behaviour. Standing snags and coarse woody debris reduced radiation input, while successional undergrowth further buffered soil warming. Maximum air temperature at 5 cm reached 32.5 °C—lower than the open area but higher than the intact forest. The soil temperature at –2 cm never exceeded 25.9 °C, confirming effective shading by both structural elements and vegetation. Notably, nocturnal minima on deadwood-dominated site showed a minor anomaly, with a temperature of 50 cm (8.8 °C) being slightly lower than at 5 cm (8.9 °C), suggesting a weak nocturnal inversion possibly caused by the shrub-herb vegetation and scattered woody debris modifying radiative exchange. During the snow-free episode (20–21 February 2025), the intact forest exhibited the lowest near-ground temperatures, with nocturnal minima reaching –14.4 °C (5 cm) and –7.1 °C in the topsoil (–2 cm; Fig. 9a). In the deadwood-dominated forest, minimum air temperature at 50 cm dropped even further (–15.8 °C), indicating a micro-inversion driven by complex stand structure (Fig. 9b). In the open area, soil minima reached –3.5 °C (Fig. 9c), consistent with strong radiative cooling under snow-free conditions. In contrast, during the snow-covered episode (10–11 March 2022), microclimatic differences largely disappeared (Fig. 10). Deep snow cover (intact forest - 96 cm, deadwood-dominated forest - 139 cm, open area - 148 cm) stabilised temperatures across all sites, maintaining soil and near-ground air above 0 °C. However, the deadwood-dominated forest exhibited slightly weaker cooling gradients in the soil compared to the intact forest, reflecting a combined insulating effect of snow and successional

vegetation. These episodes demonstrate that in the absence of snow, intact forest can paradoxically allow stronger near-ground cooling due to suppressed nocturnal ventilation. In contrast, a deadwood-dominated forest provides more effective soil buffering. Under snow cover, differences between sites diminish, highlighting snow depth as the dominant stabilising factor. Overall, the structural complexity of deadwood-dominated stands contributes to microclimatic stability, particularly during extreme conditions when canopy shielding is absent.

4 DISCUSSION

4.1 Microclimatic buffering effects of forest structure

Our results show that the microclimate on steep south-eastern slopes of the Western Carpathians is co-determined by exposure, as well as stand structure. The open area, fully exposed to shortwave radiation, exhibited the highest daily sums of global radiation and the most pronounced thermal extremes in the near-surface layer and the upper soil horizons. By contrast, the intact stand as well as the deadwood-dominated forest (hereafter “deadwood forest”) reduced the input of shortwave energy. It damped daily temperature maxima, with the deadwood forest acting as a transitional yet distinctly “buffering” state. This accords with observations by Mwamulima et al. (2025) and von Arx et al. (2012), which indicate that stand structure fundamentally influences the buffering capacity of the microclimate. Similar microclimatic buffering effects have been confirmed in

beech stands (Thom et al., 2020a). With respect to the first research question, it can therefore be stated that although the deadwood forest does not fully maintain microclimatic conditions comparable to an intact forest, it is markedly closer to them than the open area and functions as a stabilising intermediary. Indeed, in the case of summer thermal extremes, the buffering effect of the deadwood-dominated stand may exceed the capability of the living forest.

4.2 Influence of exposure and near-surface layers

Exposure (slope and aspect) markedly amplifies and modulates the temperature regime. At 2 m height, mean air temperature in the open area exceeded that at the Červenec reference station ($\sim 3.9^\circ\text{C}$ for the same period), despite only ~ 55 m elevation difference. Using a standard lapse rate (0.65°C per 100 m), $\sim 0.36^\circ\text{C}$ ($\approx 47\%$) of the 0.76°C deviation is explained by elevation, leaving $\sim 0.40^\circ\text{C}$ ($\approx 53\%$) attributable to south-eastern exposure ($\sim 25^\circ$). This interpretation is consistent with the framework proposed by Stage and Salas (2007), who demonstrated that elevation, slope, and aspect interactively determine site energy balance. Further support comes from comparing air vs. soil temperature differences: while the mean open–intact difference was 0.79°C at 2 m and only 0.57°C near the ground surface, it reached 1.34°C at -2 cm and remained 1.24°C at -10 cm. This indicates that air temperature contrasts are consistently smaller than soil contrasts. Similar findings are summarised by Geiger et al. (2009), who reported that soil is more directly influenced by solar radiation and energy storage, whereas near-surface air is more effectively mixed by convective flows, reducing temperature gradients. Taken together, these results confirm the decisive role of “exposure climate” in shaping microclimatic dynamics on slopes, in line with broader observations on mountain environments (Barry, 2008). On the basis of our data, it may be assumed that this exposure signal is transmitted towards the surface and interacts with the properties of the active surface: at 5 cm above ground and in the upper soil layers (-2 to -5 cm) the open area had the highest means and the most pronounced summer maxima (e.g. $\sim 49^\circ\text{C}$ at -2 cm in soil; $\sim 34^\circ\text{C}$ at 5 cm above ground), whereas both forest types remained distinctly cooler. Ecologically, this difference is significant because regeneration in the earliest developmental phases is exposed to the lowest layers of the atmosphere and soil, where the combination of heat and VPD fundamentally influences stomatal conductance, assimilation, and the water regime. Similar results are provided by John et al. (2024), who point to the stand’s influence on moderating microclimatic conditions during extreme summer heat. This general buffering pattern, however, does not exclude local vertical anomalies within the deadwood-dominated structure. The occasional higher summer maximum air temperature at 50 cm in the deadwood-dominated forest compared with the open area may be explained by the presence of a structurally dense and thermally active layer at this height, formed by fallen branches, downed stems, deadwood surfaces, and successional herbaceous vegetation. During hot days, these surfaces may absorb radiation and locally heat the adjacent air, whereas the open area lacks such an elevated thermally active layer at 50 cm or 200 cm.

4.3 Incoming solar radiation and sunflecks

The deadwood-dominated forest measurably altered the incoming shortwave radiation by limiting the direct impact of solar beams through a combination of standing snags, broken stems, and dense herb-shrub succession. This was clearly demonstrated

by transmittance values and their temporal variability, corresponding to the “patchy” light field (sunflecks) cast by standing dead structures. This diffusive effect transforms the incident beam into spatially and temporally dispersed radiation, thereby reducing peak soil heating relative to the open area and often keeping the -2 cm layer below thresholds associated with thermal damage (Atkin et al., 2000) to fine roots and germinating seedlings. This diffusive effect has been also described by Eliáš (2014). On the analysed clear summer day, the deadwood forest did not display the short, intense soil-heating events that occurred in the intact forest during midday sunflecks; the shade of snags and the successional understorey prevented direct illumination of the soil for most of the day. However, we acknowledge that our measurements of incoming global radiation were conducted at a height of 2 m, which is suitable for discussing the impact and transmissivity of solar radiation through the main canopy layer or the layer of standing dead trees. To assess in more detail the influence of the multi-layered herbaceous strata within the deadwood-dominated stand, it would have been necessary to measure light transmissivity not only at 2 m, but also at representative heights of all vegetation layers, and especially near the ground. Unfortunately, for technical reasons we were not able to achieve such measurement detail, and we therefore clearly recognize this as a limitation of our study, leaving this issue to be addressed in future research.

4.4 Thermal and vapour pressure deficit (VPD) stress

These radiation–thermal differences translated into biologically meaningful contrasts in moisture stress. In summer, at 5 cm above the surface, exposure to $\text{VPD} > 1.5$ kPa lasted on average ~ 9.8 h day^{-1} on the open area, ~ 7.3 h day^{-1} in the deadwood forest, and ~ 3.9 h day^{-1} in the intact forest. Daily VPD maxima were ordered similarly (open > deadwood > intact). The deadwood-dominated site does not fully match the results achieved in the intact forest. However, it reduces exposure to high VPD by approximately half compared with the open area, specifically in the stratum where seedlings actually experience it. Together with lower soil maxima, this increases the potential for establishment and survival of natural regeneration in the deadwood forest compared with a completely deforested area. These differences reflect known mechanisms whereby forest stands substantially dampen daily extremes of temperature and VPD, as documented in the review by Thom et al. (2020b). Under conditions of limited soil water, stomata close nearly permanently to prevent drought-induced hydraulic failure, thus reducing carbon assimilation (McDowell et al., 2008). Even when soil water is sufficient, isohydric species such as spruce exhibit stomatal closure in response to high VPD (Kurjak et al., 2012). Moreover, extreme temperatures can alter cuticular wax properties and decrease their viscosity, thereby enhancing cuticular conductance (Riederer and Schreiber, 2001). As a result, one of the plant’s key protective mechanisms against excessive water loss becomes impaired under conditions of extreme heat and drought (Wang et al., 2024). Thus, the second research question is addressed: retained standing and downed wood create conditions clearly more favourable than the open area, and ecologically much closer to an intact stand.

4.5 Winter buffering mechanisms

The analysis of winter episodes illuminated the different buffering mechanisms of the studied sites against negative thermal extremes. Under snow-free conditions, minima at 5–50 cm in the intact forest reached very low values, which were related

to suppressed nocturnal ventilation and the accumulation of cold air under a closed canopy. By contrast, the deadwood forest exhibited a slight thermal micro-inversion up to 50 cm height and, importantly, warmer minima at the soil surface than the intact forest. Although we did not have direct measurements of air flow, von Arx et al. (2012) clearly demonstrated that air movement declines substantially in a closed forest compared to an open area. We therefore adopt these conclusions and use them to explain why the near-surface atmosphere and soil in the intact forest cooled strongly at night, even though the same site warmed most markedly during the day. With snow cover, differences between sites diminished, and snow insulation dominated; however, a milder cooling gradient in the soil persisted, favouring the deadwood forest. The combination of dead woody material, coarse debris, and a moist successional understorey thus modifies radiative exchange and nocturnal coupling with the atmosphere, stabilising the microclimate relevant for seedlings and soil biota. Similar results indicating the insulating influence of snow cover are documented by Brůna et al. (2024).

4.6 Hydrological and Management implications

Although we did not directly measure soil moisture, several microclimatic indicators suggest potentially more favourable hydrological conditions in the deadwood-dominated forest than in the open area: lower radiative and thermal peaks imply lower atmospheric evaporative demand, and shorter durations of high VPD indicate reduced near-ground atmospheric drought stress. In addition, the structural roughness of retained deadwood and understorey vegetation may improve micro-site water retention and infiltration of precipitation, consistent with studies describing deadwood as an important recipient and regulator of water (Green et al., 2022; Floriancic et al., 2023). However, this interpretation must be made cautiously. Retained deadwood and dense successional understorey may also increase interception storage, particularly during small precipitation events, and may therefore temporarily reduce the amount of water reaching the soil surface. Previous studies from subalpine spruce stands in the Western Tatras have shown that interception strongly affects the redistribution of precipitation beneath spruce canopies (Jančo et al., 2021) and may influence surface runoff in declining mountain spruce forests (Jančo et al., 2026). Consequently, the net effect of deadwood retention on soil moisture and catchment water balance cannot be inferred from microclimatic indicators alone. It should be verified by direct measurements of throughfall, interception, soil moisture, surface runoff, and snowmelt contribution.

There are three management implications. (i) On exposed mountain slopes, the “exposure climate” is a primary source of risk: clear-felling or intensive salvage logging that removes shading elements maximises solar input at the surface and thus often exceeds thermal and VPD thresholds in the near-surface layer that are physiologically tolerable for natural or even targeted forest regeneration. (ii) Retaining deadwood—standing snags and downed stems—and allowing the development of a successional understorey creates a demonstrable microclimatic barrier: lower daytime maxima of air and soil, shorter and weaker VPD peaks, and more stable winter conditions at the surface. These effects directly widen the “survival window” of natural regeneration under the current climate and even more so with the expected intensification of atmospheric dynamics. In this sense, deadwood retention may also influence the trajectory of natural succession in mountain spruce forests. By reducing near-ground temperature extremes and VPD while maintaining a

heterogeneous light environment, retained deadwood and successional understorey can create microsites favourable for Norway spruce regeneration, which represents the natural dominant component of this ecosystem. However, this effect is spatially variable, as dense understorey vegetation may locally increase competition for light, water, nutrients, and space. Although fungal and saproxylic organisms were not directly analysed in this study, our results suggest that future assessments of biological processes associated with retained deadwood may benefit from considering near-ground and soil microclimatic conditions, as standard 2 m measurements may not fully capture biologically relevant microsite contrasts (Středa et al., 2011). Thus, deadwood retention should be viewed not as a uniform improvement of regeneration conditions, but as a mechanism creating a mosaic of microsites that may support ecosystem self-organisation and stability after disturbance. Similar findings were published by Zhang et al. (2024) for boreal forests. (iii) The frequent argument of higher fire risk when deadwood is retained, documented for example by Ruthrof et al. (2016), must be assessed in the context of the documented microclimate. Fire hazard should therefore be considered as part of abiotic risk assessment in disturbed mountain forests. Previous multi-hazard assessments for Central European Forest ecosystems have mainly focused on drought, high temperature, and wind-related risks (Středová et al., 2020), whereas fire danger may become relevant where surface fuels, near-ground drying, and high atmospheric demand interact. Our data do not allow us to recommend or validate a single universal fire-resistance index, because fuel moisture, ignition probability, and fire behaviour were not measured directly. However, the results indicate that future fire-hazard assessments in deadwood-dominated mountain spruce stands should include near-ground VPD, near-ground air temperature, relative humidity, and, where possible, fine-fuel or surface-vegetation moisture, rather than relying only on standard 2 m meteorological variables. In our conditions, luxuriant, water-holding successional vegetation and persistent shading suppress fuel desiccation and reduce near-surface temperatures compared with the open area. The removal of wood does not, by itself, necessarily minimise risk; decisive factors are fuel moisture, fuel structure, and microclimate. If material is not removed “to the last splinter”, open areas may paradoxically host finer and faster-drying fuels while simultaneously experiencing warmer, drier conditions than shaded deadwood plots. This is consistent with the fire-risk assessment performed for the study region (Škvarenina et al., 2024). In this context, the argument that fuels for spring fires on exposed slopes consist primarily of desiccated biomass of successional vegetation does not fully apply, because in mountain regions—even on exposed slopes of the Western Tatras—there is usually a thick snow cover until late May (Bartík et al., 2019), which limits the spring fire season; in snow-free years, near-surface biomass may still be exposed to low air temperatures and frost events, as indicated by the climatic analysis in this paper.

In conclusion, a changing climate reconfigures the debate over intervention versus non-intervention in mountain forests. Mountain ecosystems that relied upon (and were therefore shaped during ecosystem formation to fit) a robust macroclimate may, in cases of extreme weather situations, be moderated by microclimate—determined by micro-relief, residual structure, and surface cover—which should be utilised in the management of mountain ecosystems under conditions that require effective adaptation to climate change.

4.7 Generality of the observed mechanisms

The broader relevance of our findings lies primarily in the mechanism rather than in the direct transferability of the measured values. The specific magnitude of the buffering effect observed at Červenec is site-dependent and reflects the south-eastern exposure, steep slope, elevation, snow regime, and the particular structure of the deadwood-dominated stand. However, the underlying processes are more general: exposure climate affects the radiation balance and, consequently, the thermal and moisture regime of near-ground air and soil on mountain slopes. Deadwood, standing snags, downed logs, and successional understorey vegetation can modify this exposure-driven signal by creating shade, increasing surface roughness, reducing direct shortwave radiation at the ground, and altering near-surface air exchange. Therefore, our results should not be interpreted as universally transferable numerical thresholds, but as evidence that post-disturbance structural complexity may mediate the effect of exposure climate on regeneration-relevant microclimatic conditions.

5 CONCLUSIONS

This study demonstrates that deadwood-dominated forests not only approximate the microclimatic buffering capacity of intact spruce stands, but in several respects even exceed them. Particularly during summer heat episodes, deadwood stands reduced extreme soil and near-ground air temperatures more effectively than intact forests, owing to the combined effects of standing snags, coarse woody debris, and successional ground vegetation. Thus, with regard to our research questions, deadwood-dominated forests maintain microclimatic conditions that are clearly closer to those of intact forests than those of open areas. Under certain circumstances, they provide even stronger buffering against extremes that threaten seedling survival and soil functioning. These findings carry important implications for forest management in mountain regions facing rapid climate change. Conventional salvage logging creates open areas that maximise radiation and atmospheric coupling, exposing regenerating forests to stressful thermal and hydric conditions. By contrast, retaining dead and fallen trees allows self-organising processes to generate protective microclimates that reduce stress and extend regeneration windows. It may also contribute to improved hydrological functioning in headwater catchments. If confirmed by further research, this suggests that unmanaged post-disturbance stands should be recognised not only as ecological refugia but also as functional landscape components with microclimatic, eco-stabilising, and water-regulating roles. Nevertheless, our experiment was limited in spatial scope, replication, and direct hydrological data. Broader, long-term studies including soil moisture monitoring and multiple mountain expositions are needed to validate and generalise these conclusions. However, the current evidence already highlights that retaining deadwood represents a low-cost, ecologically grounded adaptation strategy. In an era of intensifying atmospheric dynamics, such strategies may be indispensable to maintain the persistence and resilience of high-mountain forest ecosystems.

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